

Multi-mission observations of the old nova GK Per during the 2015 outburst

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The remarkable old nova and an intermediate polar (IP) – GK Per was observed with *Swift*, the *Chandra* HETG and *NuSTAR* during its recent dwarf nova (DN) outburst in March – April 2015. Monitoring the outburst, we noticed several processes occurring on different time scales, such as: the slow evolution of the very soft X-ray emission (below 0.6 keV) during the first two weeks of the outburst and the very fast saturation of the X-ray flux above 1 keV. The *Swift* UVOT lights curves also showed different behaviour, depending on the filter. The broad band X-ray spectra revealed the presence of at least three different emitting sources. The white dwarf (WD) spin was observed even in the very hard X-ray range of *NuSTAR*, indicating that the modulation is not due to absorption, in contrast to a typical IP. It is also supported by the similarity of the on-pulse and off-pulse X-ray spectra. We propose that the scenario when the inner accretion disk pushed towards the WD by the increased accretion obscures the lower WD pole can work also for GK Per.

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1. Introduction

GK Per underwent a nova explosion on 1901 February 21 [1] and after a long period of irregular fluctuations, in 1948, it started to behave like a DN, with a small amplitude (1 – 3 mag.) outbursts lasting for up to two months, repeated every $\simeq 26$ months [2]. The most widely accepted explanation of these outbursts is a repeating thermal instability in the inner part of the accretion disk (inside-out outbursts; see [3], [4] for application of the disk instability to GK Per). GK Per hosts a magnetic WD (first proposed by [5] and [2]), and, hence, the accretion disk is truncated by the magnetosphere of the WD that surprisingly does not prevent the instability. Watson et al. first discovered the X-ray modulation with the period of 351 s, related to the WD spin [6]. The authors noticed that the pulse fraction is remarkably constant — 50 % and only at 3 keV is up to 80 %.

The orbital period is quite long – 1.997 d [7] and the distance to the object is well defined – 470 pc [8]. The secondary is a K2 type subgiant with the mass of $0.25 M_{\odot}$ ([9], [6]) and the mass of the primary is $\leq 0.72 M_{\odot}$ [6].

On 2015 March 6.84 Dubovsky (VSNET-ALERT 18388) and Schmeer (VSNET-ALERT 18389) discovered that GK Per has started a new DN outburst and was at a magnitude 12.8. We proposed a multimission observation campaign in order to follow the evolution of the object during the outburst and to obtain X-ray spectra in a broad energy range, revealing the physical processes that take place in this binary system.

2. Observation and data analysis

We started the observations of the 2015 DN outburst of GK Per as soon as it became visible for *Swift* – on March 12 2015 and observed it almost until optical maximum. We obtained two exposures per day with *Swift* for two weeks and one exposure per day for another two weeks. Coordinated *NuSTAR* and *Chandra* Advanced Imaging Spectrometer High-Energy Transmission Grating (ACIS-S/HETG) observations were performed on April 4 2015, close to the optical maximum. The *Swift* X-Ray Telescope (XRT) and Ultraviolet Optical Telescope (UVOT) data were processed with the *ftools* package. We used the processed *Swift* Burst Allert Telescope (BAT) data from the *Swift* BAT transient monitor page [10]. We reduced the *Chandra* data with CIAO v.4.7 and the *NuSTAR* data with the standard *nuproducts* pipeline. All the light curves were extracted after the barycentric correction. The X-ray spectra were analysed and fitted using XSPEC v. 12.8.2. The list of the observations with the exposure times and count rates is presented in Table 1.

3. Results

The long-term light curves in optical, ultraviolet (UV) and X-rays are presented in fig. 1. The optical light curve was obtained from the AAVSO¹. The *Swift* XRT count rate was variable by $\sim 50\%$ but with no significant increasing or decreasing trend. We probably missed a steep rise of the X-ray count rate, which is usually observed in the first days of the outburst in GK Per (see [11] for the comparison of the previous eight DN outbursts of GK Per). The high energy light curve of *Swift* BAT is more stable and only shows a moderate decrease after reaching maximum around day

¹American Association of Variable Star Observers: www.aavso.org

Table 1: Observational log

Instrument	Date ^a	Exp.(s)	Count rate ^b
<i>Swift</i> XRT	57093.15 – 57121.06	373.6 – 2401.5	0.67 – 2.14
Chandra MEG	57116.83	69008	0.0751±0.0010
Chandra HEG	57116.83	69008	0.1214±0.0013
NuSTAR FPMA	57116.12	42340	3.665±0.009
NuSTAR FPMB	57116.12	42340	3.626±0.009

Notes.^a Modified Julian Date. ^b The count rates were measured in the following energy ranges: *Chandra* Medium Energy Grating (MEG) - 0.4–5.0 keV, *Chandra* High Energy Gratings (HEG) - 0.8–10.0 keV, *NuSTAR* Focal Plane Modules A and B (FPMA and FPMB) - 3–79 keV.

10 after the outburst (AO). It also suggests the outburst may have started 2 days earlier in the *Swift* BAT energy range than in optical. The hardness ratio (HR) revealed a gradual softening of the X-ray spectrum, with minimum around 20 days AO. The X-ray radiation reaches a plateau already in several days AO, while the optical emission is not saturated at all. The *Swift* UVOT light curves in different filters (the second panel of fig. 1) are very different from each other: the U filter light curve is like the hard X-ray light curve, while the UVM2 light curve mimics the optical one.

3.1 Timing analysis

For our timing analysis we extracted the X-ray light curves from the *Swift* XRT, *NuSTAR* and *Chandra* observations. In order to investigate a possible energy dependance of a variability we subdivided the *Swift* XRT light curves in two energy ranges: 0.3–1.5 keV and 1.5–10 keV and the *NuSTAR* light curves were extracted below and above 10 keV. We binned the *Swift* light curves every 30 s and the *NuSTAR* light curves every 10 s, subtracted the linear trends and performed the timing analysis using the Lomb-Scargle method [12]. The Lomb-Scargle periodogramms (LSPs) in a broad range of periods are presented in the right panels of fig. 1. There are very strong spikes in the *Swift* and *NuSTAR* LSPs, which correspond to the same period – 351.35 s. We see from the long term *Swift* XRT light curve that the mean count rate varied from observation to observation. Since each exposure covered at least two spin periods this variability is not due to the different spin phases. Aiming to remove the contribution from this long-term variability, we normalized each individual *Swift* light curve in the harder energy range to the mean value of the count rate within the exposure, combined the light curves and calculated the LSP again. The period we found is the same – 351.35±0.02. The peak-to-peak pulse amplitude is ~ 10 cts s⁻¹ in the *NuSTAR* data and ~ 1 cts s⁻¹ in the *Swift* XRT data, however, the pulse fraction is the same in both observations – about 50%.

The bottom-right panel of fig. 1 shows the phase folded *NuSTAR* light curves in two energy ranges: 3–10 (red) and 10–79 (black) keV. The modulation is present even in the harder range and the spin profiles are almost identical. There is a hint that in the hard X-rays the pulse profile is double-peaked. Typically the spin modulation is not observed in the hard X-rays, since the cross section of the photoelectric absorption that causes the modulation decreases with energy. A possible mechanism of the pulsations in GK Per will be discussed later.

The LSP of the soft *Swift* XRT light curve (the red dashed line in the top-right panel of fig. 1) shows a strong spike at 5765 s. Several authors also reported quasi periodic variability on timescales of kiloseconds (e.g. [6], [13], [14]).

We extracted the light curves from the *Chandra* HETG data in the regions of the strongest emission lines of Mg, Si and Fe $K\alpha$ and checked whether the flux in these lines is modulated with the orbital or with the spin period. We found that only the Fe $K\alpha$ line emission shows pulsations with the spin period. The other lines do not show any measurable periodical modulation, however the flux is quite variable.

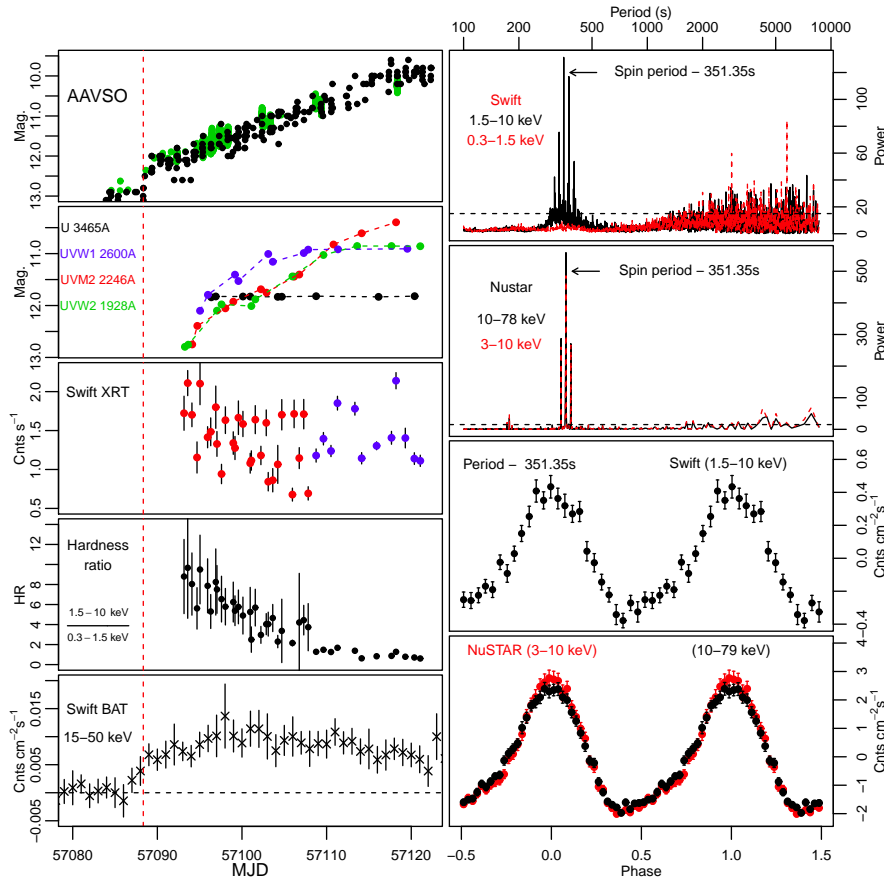


Figure 1: Left (from top to bottom): AAVSO light curve in the V band (green) and without filter (black). The red vertical line marks the beginning of the outburst in the optical band in all the panels. The *Swift* UVOT light curves in different filters. The *Swift* XRT light curve in the photon counting (red) and window timing (blue) modes. The hardness ratio. The *Swift* BAT light curve. Right (from top to bottom): The LSPs of the *Swift* XRT light curves below 1.5 keV (the red dashed line) and above 1.5 keV (the black line). The LSPs of the *NuSTAR* light curves below 10 keV (the red dashed line) and above 10 keV (the black line). The *Swift* XRT light curve above 1.5 keV folded with the WD spin period. The *NuSTAR* light curves below 10 keV (the red points) and above 10 keV (the black points) folded with the WD spin period.

3.2 X-ray spectra

In fig. 2 we present the X-ray spectra from all the instruments. The top-left panel shows the

combined *Swift* XRT spectra: the black line is the spectrum integrated over the first two weeks of the observations and the red line – over the next two weeks. The main difference between them is in the very soft range, below 0.6 keV, which also explains the HR curve (see fig. 1). The combined *Chandra* HETG and *NuSTAR* spectra are presented in the top-right panel of fig. 2. This broad band spectrum has three distinct regions, which show different properties. The best fitting model that we applied consists of a blackbody and a two-temperature thermal plasma emission, highly absorbed by the partially covering absorber. The blackbody component has a temperature of ~ 25 eV. Although the thermal plasma model can marginally represent the shape of the continuum in the 0.8 – 4 keV range it fails to fit the emission lines in the *Chandra* HETG data. The line ratios in the helium-like triplets of Ne, Mg and Si and the fact that emission from the He-like ions is stronger than from the H-like ions indicates that the emitting plasma is not collisional ionized and there is a possible contribution from the photoionization processes [15]. The hard part of the spectrum is well represented by the thermal plasma emission at the temperature of 14 keV, but requires a very high value of absorption of the order of 10^{24} cm $^{-2}$. We also extracted the on-pulse and off-pulse spectra from the *NuSTAR* observations. The shapes of the spectra were almost the same and only require different emission measures of the thermal plasma emission in the best-fitting model. It confirms the assumption that the spin modulation of the X-rays is not due to absorption.

4. Discussion

Mauche analysed all the available estimates of the WD spin period in GK Per and found a possible decreasing trend, indicating that the WD in GK Per is spinning up [16]. We compared our measurements of the spin period with the predictions of this trend and found that our values are much longer. We also re-analysed the *Swift* XRT and UVOT observations of GK Per, obtained during the 2012 DN outburst and found the same value of spin the period – 351.35 s, which is not consistent with the predicted trend.

The presence of the spin modulation in the very hard X-rays indicates that it is not due to absorption in the accretion column, like in a typical IP. Hellier et al. proposed that in the eclipsing IP, XY Ari, increased accretion pushes the inner accretion disk inwards, blocking the visibility of the secondary accreting pole [17]. As a result, during the DN outburst we see only the primary accretion column, and the visibility depends on the WD spin phase. This model may also explain our GK Per observations.

The broad band X-ray spectra revealed the presence of three distinct regions: very soft emission at $T_{\text{bb}} = 25$ eV, absorbed with only interstellar absorption, emission in the range 0.8 – 4 keV, with a possible impact from the photoionization processes and a highly absorbed thermal plasma emission at $T=14$ keV. Only the third component of the spectrum shows modulation at the spin period. The origin of the very soft component that gradually develops during the explosion is an open question.

5. Acknowledgements

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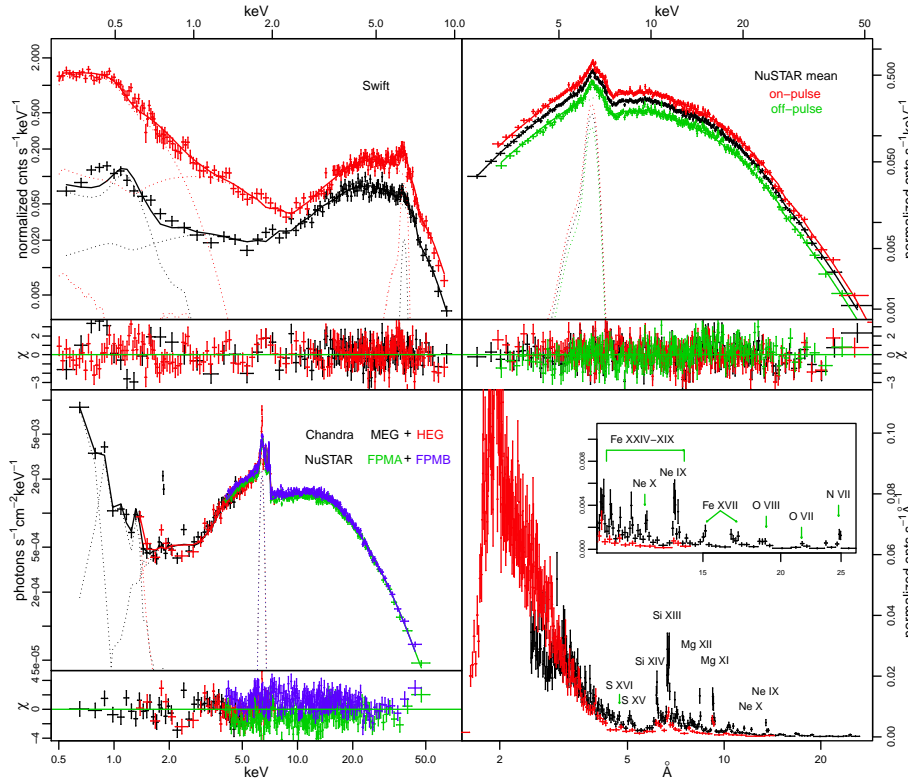


Figure 2: Top-left: The *Swift* XRT spectra, integrated over the first two weeks (black) and the following two weeks (red) of the observations. Top-right: The *NuSTAR* FPMA mean (black), on-pulse (red) and off-pulse spectra. Bottom-left: The combined *Chandra* MEG (black), HEG (red) and *NuSTAR* FPMA (green) and FPMB (blue) spectra. In all these three panels the solid lines show a preliminary fit with the following model in XSPEC – $wabs \times (bb + pcfabs \times pcfabs \times (apec + apec + gauss))$. The dashed lines show the model components. Bottom-right: The *Chandra* MEG (black) and HEG (red) spectra with the identified emission lines.

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DISCUSSION

VOITEK SIMON: Did you detect any changes of the profile and amplitude of the spin modulation with the progress of the outburst of GK Per?

POLINA ZEMKO: We tried to sum up every 5 observations, extract the light curve above 1.5 keV, remove the trend and to fold the resultant light curves with the spin period. The amplitude of modulation was stable, but the spin profile became more smooth with time.